Recent Progress Towards the Seismic Control Of Structural and Non-Structural Systems in Hospitals

by

A. Filiatrault, G. Lee, A. Aref, M. Bruneau, M. Constantinou, A. Reinhorn and A. Whittaker
Multidisciplinary Center for Earthquake Engineering Research (MCEER)
State University of New York at Buffalo
Buffalo, NY 14260

ABSTRACT

The main objective of this research is to develop a better understanding of the applications of various seismic response modification technologies to protect structural and nonstructural systems and components in acute care facilities from the effects of earthquakes. A secondary objective of the research is to establish a relationship between the performance of nonstructural components and structural demands in order to optimize and harmonize performance objectives between structural and nonstructural systems and components in acute care facilities. A broad range of seismic response modification technologies are under investigation, from those close to implementation to others that require long-term investigation. Results of analytical and experimental studies are being used in fragility studies to probabilistically quantify the relative merits and potential benefits to structural and nonstructural component of implementing these technologies. Eventually, the results will be quantified and included in decision support methodologies that integrate both engineering and social science aspects.

1.0 INTRODUCTION

Achieving a given target seismic resiliency for acute care facilities require the harmonization of the performance levels between structural and nonstructural components. Even if the structural components of a hospital building achieve an immediate occupancy performance level after a seismic event, failure of architectural, mechanical, or electrical components of the building can lower the performance level of the entire building system. This reduction in performance caused by the vulnerability of nonstructural components has been observed in several buildings during the recent 2001 Nisqually earthquake in the Seattle-Tacoma area (Filiatrault et al. 2001) and during several other earthquakes that have occurred in the last 40 years (Ayres et al. 1973, Ayres and Sun 1973, Ding et al. 1990, Reitherman 1994, Reitherman and Sabol 1995, Gates and McGavin 1998). Figure 1 taken after Miranda (2003) illustrates the typical investments in structural framing, nonstructural components and building contents in office, hotel and hospital construction. Clearly the investment in nonstructural components and building contents is far greater than that of structural components and framing. Therefore, it is not surprising that in many past earthquakes, losses from damage to nonstructural building components exceeded losses from structural damage. This was clearly the case in the recent 2001 Nisqually earthquake (Filiatrault et al. 2001). Furthermore, failure of nonstructural building components could become safety hazards or could affect the safe movement of occupants evacuating or rescue workers entering buildings.

In comparison to structural components and systems, there is still relatively limited information on the seismic performance of nonstructural components. Basic research work in this area has been sparse, and the available codes and guidelines (FEMA 1994, ASCE 2000, Canadian Standard Association 2002) are usually, for the most parts, based on past experiences, engineering judgment, and intuition, rather than on experimental and analytical results. Often, design engineers are forced to start almost from square one after each earthquake event: observe what went wrong and try to prevent repetitions. This is a consequence of the empirical nature of current seismic

regulations and guidelines for nonstructural components.

Retrofitting hospitals using seismic response modification technologies can make it possible to harmonize the performance of structural and nonstructural components in order for entire acute care facilities to meet or exceed a specified resiliency level during and after an earthquake. The initial expense of these technologies may be considered high at first glance, but increased implementation based on sustained research efforts is expected to reduce costs in the future to the point where they will be the same or less than conventional retrofitting techniques. Furthermore, the use of seismic response modification technologies that reduce the seismic demands on nonstructural components can significantly reduce the cost of retrofitting these items that often represent the bulk of the facility investment.

Figure 2 presents, as an example, sample fragility curves for suspended ceiling systems (SCS) (Badillo et al. 2002). Failure of SCS has been one of the most widely reported types of nonstructural damage in past earthquakes. Ensembles of fragility curves were developed by MCEER researchers based on twenty-seven sets of earthquake-simulator tests on six tile-suspension systems. The specific objectives of the research program were: (1) to study the performance of a SCS that is commonly installed in the United States; (2) to evaluate improvements in response offered by the use of retainer clips that secure the ceiling panels (tiles) to a suspension system; (3) to investigate the effectiveness of including a vertical strut (or compression post) as seismic reinforcement in ceiling systems; and (4) to evaluate the effect of different boundary conditions on the response of a SCS.

It was found that the use of retainer clips substantially improved the behavior of the SCS in terms of loss of tiles but also increased damage to the suspension system. This example illustrates the fact that if the use of structural technologies can reduce sufficiently the seismic demands on SCS, these components may not need any retainer clips, or other retrofit

methodologies, to perform adequately, thereby contributing to the overall seismic resiliency of the facility.

This paper briefly describes the research currently underway at MCEER on the development of seismic response modification technologies for the seismic protection of structural and nonstructural systems and components in acute care facilities. This work is innovative and important since the application of seismic response modification technologies in building structures to date has been based solely on structural performance. Only when the variations in seismic fragility of coupled structural and nonstructural components as a function of structural systems (including seismic response modification technologies) and/or equipment retrofit is available that robust decision-making tools can be implemented.

2.0 SEISMIC RESPONSE MODIFICATION OF STRUCTURAL AND NONSTRUCTURAL SYSTEMS AND COMPONENTS USING TECHNOLOGIES DEVELOPED AT MCEER

This section present the various studies aimed at controlling the seismic response of structural and nonstructural systems and components in acute care facilities. These studies are conducted using various advanced technologies developed by MCEER researchers.

2.1 Studies on MCEER West Coast Demonstration Hospital

MCEER researchers are investigating the seismic demands on structural and nonstructural systems and components in acute care facilities through two-dimensional and three-dimensional numerical modeling of MCEER West Coast Demonstration Hospital in a variety of computer platforms. The MCEER West Coast Demonstration Hospital is an existing facility in the San Fernando Valley in Southern California (Bruneau et al. 2003). The hospital facility was constructed in the early 1970's to meet the seismic requirements of the 1970 Uniform Building Code. One particular building of the facility's campus, a rectangular four-story steel moment-resisting frame referred herein as

WC70, was selected for in-depth studies. Figure 3 shows an isometric view of the framing of the studied building. By using these numerical models, MCEER researchers are able to compute demands on nonstructural components and judge the utility and efficiency of different seismic modification technologies to reduce the vulnerability of nonstructural components. Model verification is on-going across the various computer platforms to ensure consistency of results.

The computer platform IDARC2D, developed by MCEER researchers, was used to judge the impact of plausible variations in structural-framing modeling assumptions on the demands on the nonstructural components, including modeling the non-seismic steel moment-frame connections as rigid (Model 1), semi-rigid (Model 2) and pinned (Model 3), and modeling the column base connections as rigid, semi-rigid and pinned. Nonlinear response-history analyses of the two-dimensional models were performed using 20 earthquake historical ground motion time-histories whose average spectrum matched well a 10% in 50 year NEHRP Site Class B design spectrum for Los Angeles. Figure 4 shows the target spectrum, the median spectrum of the 20 histories and the maximum and minimum spectral ordinates for the 20 histories. The fundamental periods of the building model in the transverse (short) and longitudinal directions are 0.70 sec and 0.76 sec, respectively.

Figure 5 presents the scatter in the median maximum floor displacements from response-history analysis using the 20 earthquake histories, as well as the scatter in maximum floor displacement for Model 2 for the 20 earthquake histories of Figure 2. For this building and the chosen ground motions, the dispersion due to modeling assumptions is relatively small. However, the scatter due to variations ground motion characteristics is much larger.

2.2 Studies on Metallic Energy Dissipation Systems

A previous article (Bruneau et al. 2003) summarized work done to use of light-gauge, cold-formed steel panels, in a new application (Bruneau and Berman 2003) of Steel Plate Walls (SPW) that made it possible to overcome the fact that panel thickness, using a typical material yield stress, required by a given design situation is often much thinner than plate actually available from steel mills (recall that walls having metallic infills are allowed to develop shear buckling, with lateral load carried in the panel via the subsequently developed tension field). To improve the SPW design concept and use hot rolled steels, MCEER initiated a co-operative experimental program with National Taiwan University (NTU) and National Center for Research on Earthquake Engineering (NCREE) to investigate the seismic performance of SPW designed and fabricated using low yield strength (LYS) steel panels and Reduced Beam Sections (RBS) added to the beam ends in order to force all inelastic action in the beams to those locations. It was felt that this would promote increasingly efficient designs of the "anchor beams," defined as the top and bottom beams in a multistory frame, which "anchor" the tension field forces of the SPW infill panel.

A total of four LYS SPW specimens were designed by MCEER researchers, fabricated in Taiwan, and tested collaboratively by MCEER and NCREE researchers at the NCREE laboratory in Taiwan. The frames, consisting of 345MPa steel members, were 4000mm wide and 2000mm high, measured between member centerlines. The infill panels were 2.6mm thick, LYS, with an initial yield of 165MPa. Two specimens had solid panels while the remaining two provided utility access through the panels by means of cutouts. One specimen consisted of a panel with a total of twenty holes, or perforations, each with a diameter of 200mm. The other specimen was a solid panel, with the top corners of the panel cutout and reinforced to transmit panel forces to the surrounding framing, as shown in Fig. 6. The intention of the final two specimens is the accommodation of penetrations by utilities necessary for building operation.

All specimens were tested using a cyclic, pseudo-static loading protocol similar to ATC-24. Loading history was displacement-controlled, and applied horizontally to the center

of the top beam using four actuators. A typical resulting hysteretic curve is shown in Fig. 7.

SPW buildings with low yield steel webs appear to be a viable option for use in resistance of lateral loads imparted during seismic excitation. The lower yield strength and thickness of the tested plates result in a reduced stiffness and earlier onset of energy dissipation by the panel as compared to conventional hot-rolled plate. The perforated panel specimen shows promise towards alleviating stiffness and over-strength concerns using conventional hot-rolled plates. This option also provides access for utilities to penetrate the system, important in a retrofit situation, in which building use is pre-determined prior to SPW implementation. The reduced beam section details in the beams performed as designed, as shown in Fig. 8. Use of this detail may result in more economical designs for beams "anchoring" an SPW system at the top and bottom of a multi-story frame. On-going research is focusing on developing reliable models that can capture the experimentally observed behavior, and investigating the benefits of this system on enhancing the seismic performance of nonstructural components, using the MCEER west-coast demonstration hospital (Bruneau et al. 2003) for that purpose.

As part of this work on metallic energy dissipation system, it was found appropriate to revisit the structural fuse concept proposed by many researchers in the past and investigate whether a systematic framework for optimal design could be implemented in the current context of formulating and operationalizing the seismic resilience concept. Multiple types of special devices for the passive seismic control of building response have been developed and implemented, starting in New Zealand in the late 1960s and early 1970s, and the research literature on displacement-based energy dissipation concepts and devices is extensive (e.g. Kelly et al. 1972, Skinner et al 1975, Tyler 1978, Pall 1982, Tsai et al 1993, Xia and Hanson 1992, Hanson et al. 1993, Iwata et al 2000, to name a few). Some studies have also referred to the term structural fuse concept, although the term has not been consistently defined in the past. In some cases, "fuses" have been defined as elements with well defined plastic yielding locations, but not truly replaceable as a fuse (e.g. Roeder and Popov 1977, Fintel and Ghosh 1981, and many more); in other cases, they were defined and used more in the context of reducing inelastic deformations of the existing frame and thus control damage (e.g. Whittaker et al 1989, Dargush and Soong 1995, Connor et al. 1997, Constantinou et al 1998, etc). In a few cases, for high rise buildings having long structural periods (i.e., T > 4 s), fuses were used to achieve elastic response of frames that would otherwise develop limited inelastic deformations (e.g. Wada et al. 1992, Shimizu et al. 1998, etc). Design procedures were also developed for systems with friction dampers intended to act as structural fuses (e.g. Filiatrault and Cherry 1989), but these required design validation by nonlinear time history analyses. Many of these past studies also considered seismic excitations less severe than those corresponding to the 2% probability of exceedence in 50 year level currently specified by design codes.

In that perspective, knowledge on how to achieve and implement a structural fuse concept that would limit damage to disposable structural elements for any general structure without the need for complex analyses is lacking. This would require identification of the key parameters that govern the behavior of systems having such structural fuses, and formulation of a general design approach that would make the concept broadly applicable, including for low rise buildings (e.g., single-degree-of-freedom systems). Furthermore, the existing research does not investigate the impact of introducing structural fuses on resulting floor accelerations and velocities, which can directly impact the seismic performance of non-structural components and building contents (a key consideration in establishing the seismic resiliency of acute-care facilities).

A general formulation was sought that would be applicable in any instance where passive energy dissipation devices have been implemented to enhance structural performance by reducing seismically induced structural damage (and,

indirectly to some extent, nonstructural damage). In this context, metallic dampers are defined to be structural fuses (SF) when they are designed such that all damage is concentrated on the passive energy dissipation devices, allowing the primary structure to remain elastic. Following a damaging earthquake, only the dampers would need to be replaced (hence the fuse analogy), making repair works easier and more expedient, without the need to shore the building in the process. Furthermore, SF introduce self-centering capabilities to the structure in that, once the ductile fuse devices have been removed, the elastic structure would return to its original position.

A parametric study was conducted leading to the identification of the possible combinations of key parameters essential to ensure adequate seismic performance for SF systems. Non-linear time-history dynamic analyses were conducted for several combinations of parameters, which have been chosen with the purpose of covering the range of feasible designs. Synthetic earthquakes generated to match selected target design spectrum were used. The effects of earthquake duration and strain-hardening on the seismic response of short and long period systems were also considered as part of this process.

Figure 9 presents the system response in terms of dimensionless global and local ductility charts, as a function of selected key design parameters. These charts show, as shaded areas, the regions of admissible solutions for the SF concept. Time history results and hysteresis loops are presented to verify the significance of earthquake duration and strain-hardening on the system behavior, as well as on the hysteretic energy dissipated. Viable combinations of parameters are identified and used to provide guidelines to design and retrofit systems using Unbonded Braces (UB), Triangular Added Damping and Stiffness (TADAS), and Shear Panels (SP) as metallic dampers working as structural fuses. The concept is being used to investigate also the effectiveness of Steel Plate Walls (SPW).

Further studies, as part of this research, are being conducted to investigate floor demands in

terms of velocities and accelerations, with the objective of assessing the applicability of the structural fuse concept to protect non-structural components. Future works will also focus on multi-degree-of-freedom (MDOF) systems.

2.3 Studies on the Response of Nonstructural Systems in Structures with Seismic Isolation and Damping Systems

It is desirable, but not always achievable, to design hospitals for Performance Level of either Immediate Occupancy or Operational. Seismic isolation and energy dissipation or damping, particularly as described in the 2000 and 2003 NEHRP Recommended Provisions for Seismic Regulations (FEMA 2001, 2004), may be the only proven construction technologies that can achieve these performance objectives. Early studies at NCEER showed promising performance for application of such technologies (Juhn et al., 1992). Yet, methodologies for the design of nonstructural systems to achieve these performance levels are not available.

In order to develop methodologies for the design of hospitals for the immediate occupancy and operational performance levels, it is necessary that (a) performance limits for nonstructural systems are established, and (b) the dynamic response of non-structural systems is determined. Recently completed studies on the behavior of structures with seismic isolation and damping systems (Wolff and Constantinou 2004) resulted in (a) a wealth of experimental results on systems of contemporary design, including data related to secondary system response, and (b) comparisons of analytical and experimental responses that demonstrate capability of nonlinear response history analysis methods to predict the response of nonstructural (secondary) systems.

With the verification of accuracy of methods of analysis of secondary systems in structures with seismic isolation and damping systems, MCEER investigators performed studies of the response of secondary systems with the purpose of (a) providing a comparison of performance of secondary systems in structures designed with contemporary seismic isolation and damping

systems having a range of design parameters, and (b) providing guidelines on the selection of seismic isolation and damping hardware for achieving specific performance levels.

The approach followed was based on dynamic analysis of structures with the following attributes:

(a) Range of structural systems with different stiffness (period) characteristics.
(b) Range of seismic isolation and damping systems, including lead-core, elastomeric, friction pendulum, linear viscous, nonlinear viscous and yielding steel systems.
(c) Range of parameters for each system, including parameters for upper/lower bound analysis for each particular system.
(d) Range of seismic excitations, including far-field, near-field and soft-soil motions, all represented by suites of motions having a representative average spectrum.

Analyses have been completed for structures with damping systems and are on-going for seismically isolated structures. The assessment of performance is based on response quantities of points of attachment of secondary systems (neglecting the interaction of the structure and the secondary systems), which include peak accelerations, peak velocities and spectral accelerations over a wide range of frequencies, as well as inter-story drifts.

Figure 10 illustrates two frames that represent part of the lateral force resisting system of two buildings. Both frames meet the criteria of the 2000 (also 2003) NEHRP recommended provisions for buildings without (frame on the left) and with damping systems (frame on the right, damped at 10% of critical). Note the substantial differences in the properties of the two frames (in terms of period T_1 and yield strength V_y).

Figure 11 presents calculated average (among 20 analyses) 5%-damped floor response spectra of the undamped building (red line), and of the building with the NEHRP-compliant damping system (3S-LV-10%, that is a linear viscous damping system providing a damping ratio of 10% in the first mode), as well other damping systems: two viscous systems designated LV-20% (a linear viscous system providing 20% damping ratio in the first mode), NLV-10% (a nonlinear viscous damping system providing an effective damping ratio of 10% in the first mode), and a yielding steel system, designated as YD. It should be noted that the undamped structure, the damped structure with the yielding steel system and the damped structures with the viscous systems at 10% effective damping just meet the NEHRP criteria for drift. The damped structure with the viscous system at 20% effective damping exceeds the NEHRP criteria for drift.

The results presented in Fig. 11 are valid for an excitation with far field characteristics and stiff soil conditions. However, similar results were obtained with near-field motions and motions representative of soft soils. The results on floor acceleration response spectra and on floor velocities (not presented here) demonstrate clear advantages of certain, but not all, damping systems.

Results of this nature are currently produced by MCEER researchers for a range of structural systems, damping systems, isolation systems, and ground motion characteristics. The analysis also includes determination of the upper and lower bounds of the mechanical properties of the damping and isolation hardware, and use of these bounds in the analysis.

2.4 Studies on Real-Time Structural Parameter Modification Systems

In an attempt to modify the response of the global structural system a new method for modification of response was suggested to extend methodologies proposed in the last decade (Soong, 1990). The RSPM (Real-time Structural Parameter Modification) is a semi-active nonlinear control system for reducing seismic responses of structural and nonstructural systems and components. Figure 12 illustrates the operation of this innovative system developed by MCEER researchers. The system includes a passive damper and a controlled stiffness unit. The passive damper is always

engaged to dissipate energy, but the stiffness unit is connected or disconnected based on a pre-set threshold. It is disconnected initially until a response threshold value—termed the open distance, is reached. If the relative displacement (positive or negative) becomes larger than the open distance, the stiffness unit is engaged to control the response. If, at any instant, the displacement becomes smaller than the threshold, the RSPM stiffness unit is disconnected. The semi-active control mechanism is activated only when the stiffness unit is connected. The devices are normally combined as a pair of tension and compression units working as a push-and-pull set.

The basic working principle of the semi-active system was described in Bruneau et al. (2003). MCEER research has been focused on the potential control benefit of the semi-active system over passive systems such as viscous dampers. The control effect of the semi-active system is targeted to seismic response reduction of nonlinear systems. To evaluate the seismic response behaviors in the linear and non-linear range, MCEER researchers have developed an index ratio of displacement incremental rate to the velocity incremental rate with respect of elastic responses. The mathematical definition of this ratio η is given below:

$$\eta = \frac{\max(d_{non}(t)) / \max(d_{lin}(t))}{\max(v_{non}(t) / \max(v_{lin}(t))}$$

where d_{non} and d_{lin} are the inelastic and elastic displacement responses respectively; v_{non} and v_{lin} are the inelastic and elastic velocity responses respectively.

Using one-story and a three-story frame models, numerical studies under different ductility and natural frequency show that η is greater than unity, which means that the displacement responses increase much faster than the velocity responses. This behavior confirms that the displacement-based control is more effective than the velocity-based control in inelastic structural response reduction. Figure 13 shows the variation of η as a function of ductility for the bilinear inelastic responses of a three-story

frame model. The study has also revealed that the change in η is strongly influenced by the yielding pattern (e.g. bilinear, tri-linear and continuous yielding), the natural period before and after yielding, and the ductility.

Figure 14 compares a passive damper system with a hybrid system (passive damping plus semi-active) in the three-story frame model response control. The damping device has been chosen as a linear viscous damper, for which the damping ratio is 15%. In the hybrid control system, an equivalent 15% of the structural stiffness has been assigned to the RSPM control along with an equivalent damping ratio 15% contributed from the hybrid device. The selection of the hybrid control parameters is based on the actual configuration of the devices. Since RSPM is designed as an improvement of the passive damper, a semi-active component is generally added to enhance the performance of the passive damper. To show the effect of the semi-active component in the seismic response control, the comparison is carried out to in a wide response range including: the elastic response, the yielding point and the large ductility range. Figure 14 shows that the displacement based semi-active control has non-uniform control effect. In general, at each structural yielding point, the hybrid control effect outperforms the damping system, as ductility increases, the hybrid control effect also increases faster than the passive damping system.

In summary, semi-active control strategies may be able to provide a larger control capability for seismic induced structural response reduction. In particular, they are better able to balance the difficult structural control requirements, such as limiting acceleration levels and controlling story responses, thus reducing structural response in both elastic and inelastic ranges. The above described progress will be further explored and considered for the MCEER Demonstration Hospital. It is hopeful that the semi-active control, together with other structural response technologies, will provide a much better floor response control for both linear and nonlinear response range. In turn, the reduced floor responses will result in less nonstructural component damage.

2.5 Studies on Self-Centering Systems

With current seismic design approaches, most structural systems, including those for hospital buildings, are designed to respond beyond the elastic limit and eventually to develop a mechanism involving ductile inelastic response in specific regions of the structural system. Although seismic design aimed at inelastic response is very appealing, particularly from the initial cost stand point, regions in the principal lateral force resisting system will be damaged and may need repair in moderately strong earthquakes and may be damaged beyond repair in strong earthquakes. While the principle of mitigating loss of life in a strong earthquake still prevails, resilient communities require mission-control buildings, including hospital facilities, to survive a moderately strong earthquake with relatively little disturbance to business operation. The cost associated with the loss of business operation, damage to structural and non-structural components following a moderately strong earthquake can be comparable, if not greater, to the cost of the structure itself. This implies that repairs requiring loss of business continuity should be avoided in small and moderately strong events. These issues have led the development in recent years of structural systems that possess self-centering characteristics that are economically viable alternatives to current lateral force resisting systems.

Figure 15 shows the characteristic *flag-shaped* seismic response of such a self-centering system. The amount of energy dissipation is reduced compared to that of a yielding system, but, more importantly, the system returns to the zero-force zero-displacement point at every cycle and at the end of the seismic loading.

Although several self-centering structural systems using shape memory alloys, or fluids constraint in specially build containers or spring loaded friction systems have been proposed, the Post-Tensioned Energy Dissipating (PTED) steel frame shown in Figure 16 is particularly appealing for hospital buildings. In this system, unlike traditional moment-resisting frames, the beams and columns are not welded together. As shown in Fig. 16, a post-tension (PT) self-centering force is provided at each floor by high strength bars or tendons located at mid-depth of the beam. Four symmetrically placed energy-dissipating (ED) bars are also included at each connection to provide energy dissipation under cyclic loading. These ED bars are threaded into couplers which are welded to the inside face of the beam flanges and of the continuity plates in the column for exterior connections and to the inside face of adjacent beam flanges for interior connections. Holes are introduced in the column flanges to accommodate the PT and ED bars. To prevent the ED bars from buckling in compression under cyclic inelastic loading, they are inserted into confining steel sleeves that are welded to the beam flanges for exterior connections and to the column continuity plates for interior connections. The ED bars are initially stress-free since they are introduced into the connection after the application of the PT force.

MCEER researchers are investigating the seismic response of structural systems incorporating flag-shaped hysteretic structural behavior, with self-centering capability. For a system with a given initial period and strength level, the flag-shaped hysteretic behavior will be fully defined by a post-yielding stiffness parameter and an energy-dissipation parameter. Parametric studies are being conducted to determine the influence of these parameters on seismic response, in terms of displacement ductility and absolute acceleration, which are also demand parameters for nonstructural components. The responses of the fag-shaped hysteretic systems are being compared against the responses of similar bilinear elasto-plastic hysteretic systems, representative of traditional yielding structural systems.

Figure 17 presents the time-histories of displacement, acceleration, absorbed energy for one-story elasto-plastic (EP) system and for a flag-shaped (FS4) system having the same initial natural period and 70% of the yield force of the EP system. The force-displacement responses of both systems are also compared in the figure. Note that the elasto-plastic system deforms inelastically primarily in one direction, while the

FS4 system has a similar amount of inelastic excursions in both directions. The FS4 system achieves a smaller maximum displacement than that of the EP system, while the maximum absolute accelerations are similar. The energy absorbed is considerably smaller for the FS4 system. Finally, unlike the EP system that sustains a residual displacement, the FS4 system returns to its initial zero position after the end of the earthquake.

Building structures with initial periods ranging from 0.1 to 2.0s and having various strength levels are being evaluated. Design envelopes for the post-yielding stiffness and energy-dissipation parameters will be determined in order to limit the demands that self-centering systems impose on nonstructural components to pre-determined levels.

2.6 Studies on Advanced Composite Infill Panels

One way to retrofit hospital buildings is with innovative design of infill walls. Even though infill construction has been popular since late 19th century in seismic regions of central and eastern United States, it is not until recently that polymer matrix composite (PMC) materials have received attention. Previously structural frames infilled with unreinforced brick, concrete masonry, and structural clay tile dominated the industry. With the infrastructure of older constructed building reaching a stage where there is significant deterioration and questionable functionality, many researchers have turned to more innovative strengthening schemes to improve on the disadvantages associated with traditional strengthening techniques. These modern rehabilitation techniques are needed to help simplify the construction process by reducing time, cost and inconvenience of associated with seismic retrofitting.

Fiber reinforced polymer (FRP) materials have increasingly been evolving as a viable seismic retrofit strategy. The ability to use FRP material in the construction of infill walls is a great advantage. Prefabricated PMC infill systems have properties that can be tailored to achieve desired response. Geometric configurations are able to remain unchanged with the option to enhance structural performance by just changing fiber orientation and stacking sequence. In a structure seismically retrofitted with PMC infill walls, ductile behavior can be achieved through shear deformation of the walls instead of plastic hinge formation. This allows the functionality of structures following a seismic event due to the fact that the gravity load carrying system will not have damage that is irreparable.

This phase of the research builds upon the research of Jung (2003) and applies it to the MCEER demonstrations hospitals. The main scope is to develop a simplified spring-dashpot model for the outer damping panel PMC infill system proposed so that dynamic analysis of the hospital structures can be performed with relative ease and with reduced computation time. The proposed model should produce sufficient energy dissipation and ductility while keeping floor accelerations at a minimum. The outer damping panel system is made of FRP panels with an interface containing both flexible honeycomb and solid viscoelastic materials. Figure 18 shows a detail of the system. Combining viscoelastic materials with honeycomb at the interface between panels has proven to be effective damping application and adding stiffness to the structure (Aref and Jung, 2003).

To evaluate the effectiveness of the PMC infill system, a moment-resisting frame from the MCEER West Coast Demonstration Hospital described earlier is considered. A finite element model of the frame was created with the damping panels in the middle three bays, as shown in Figure 19. Cyclic analysis was then performed on the facility using the ABAQUS software package. Resulting global lateral force vs. displacement hysteresis loop of the structure is shown in Fig. 20.

At this stage of the research, two fundamental issues are being considered: (1) the need for a robust visco-elastic model that efficiently works within dynamic analysis in ABAQUS; (2) the need for optimizing the size, distribution of the panels to get the proper modification to the floor

accelerations and displacements in each demonstration structure.

2.7 Studies on Global Retrofit of Structures by Weakening and Damping

Another innovative approach developed by MCEER researchers to control the seismic response of structural and nonstructural systems and components consists of weakening existing structural components to reduce maximum acceleration response, while adding energy dissipation systems (dampers) to control increased deformations (Viti et al. 2002). The method addresses simultaneous reduction of structure accelerations and structure deformations. The effect of the weakening method can be viewed as similar to the effects of base isolation solutions, which decrease the global acceleration response of structures while increasing overall movement of the structure. However, the weakening is not sufficient and requires control of deformations. The proposed solution requires modification of some of the structural components. The structures constructed with plain, or perforated shear walls, have usually high strength and develop large accelerations during earthquakes leading to damage of equipment and non-structural components.

Typical vulnerable hospital structures of this type are constructed mostly with walls with openings for windows or access doors (identified herein as perforated walls). In an attempt to evaluate their behavior before and after applying the retrofit suggested above a new modeling technique has been developed by MCEER researchers. According to the proposed technique it is suggested to model such walls using a combination of frame models with deep beams and column elements with rigid connection panels as shown in Fig. 21.

However such models for "deep" beams and columns, which exhibit a strong interaction between their bending (flexure) and shear inelastic mechanisms, are not available in customary inelastic analysis computational platforms. MCEER researchers developed such models and implemented them in the inelastic

structural analysis program IDARC2D leading to a new Version (5.5) available to the MCEER Users Network and to the specialized Users Group.

Deep beam and column elements can be expressed by a serial spring combination of shear and flexural stiffness, representing nonlinear behavior, as shown in Fig. 22. Each bilinear nonlinear spring mechanism is using friction and linear spring elements to model the elastic stiffness and the sudden transitions to post yielding stiffness.

There is only one difference between deep beam and deep column elements: the "deep" column element can resist also axial loads. In the elastic range, the initial stiffness in shear ($(1-\alpha)K_s + \alpha K_s = K_s$) and flexure ($(1-\beta)K_f + \beta K_f = K_f$) are operating. Note that α is the ratio of yield to initial *shear* stiffness (K_{sy}/K_s); β is the ratio of yield to initial *flexural* stiffness (K_{fy}/K_f). When yielding occurs in shear, flexure, or both, the friction elements are sliding maintaining the yield force constant. The post yield (sliding) stiffness of each system is govern by the shear (αK_s) or flexural (βK_f) springs in parallel with the sliders. At this stage, the springs in series with the friction-sliders do not deform at all and do not contribute to any force increase.

An extensive verification of this approach was performed by MCEER researchers using a typical wall with openings (Fig. 23) from a Californian hospital which needs retrofit through weakening. The model of the wall was analyzed with an increasing amplitude cyclic load and the performance was recorded in terms of force displacement evolution (Fig. 24) and damage progression. The performance shows a sharp reduction in the force capacity of the wall due to local shear of peers between openings and some flexural yielding at first floor. The damage indices calculated by the IDARC2D ver. 5.5 suggest that extensive damage is expected in the first floor although the strength of the wall is high.

The analytical tool developed MCEER researchers enable evaluation of the wall structure and provides way to determine the amount of strength reduction. The platform IDARC2D can then evaluate the influence of both weakening and the contribution of added energy dissipation systems.

3.0 MCEER RESEARCH INTEGRATION TOWARD ENHANCING SEISMIC RESILIENCE OF NONSTRUCTURAL SYSTEMS AND COMPONENTS

With the objective of enhancing the knowledge in the seismic performance and fragility of nonstructural components, MCEER is planning to intensify its experimental studies on the seismic performance and fragility of nonstructural components in acute care facilities. The general research methodology can be broken down into 5 distinct phases that will start with Year 8 research activities, as described below.

3.1 Generation of Ensembles Strong Ground Motion Records

Ensembles of synthetic strong ground motions representative of the range of seismic hazard levels for a given region will be generated. The ground motions will be selected based on the de-aggregation of the seismic risk for a given region in terms of most-likely magnitude-epicentral distance scenarios. The analytical strong ground motion model for Eastern and Western United states developed at MCEER by Papageorgiou (2001) will be utilized to generate the strong ground motion records. This ground motion model is described in another paper of this Research Accomplishment Volume. Two specific sites will be considered in this study corresponding to the two MCEER demonstration hospitals located in Southern California and New York State, respectively.

3.2. Generation of a Floor Acceleration Database

A floor acceleration database for the two demonstration hospitals will be generated based on time-history dynamic analyses of various structural framing systems of these two structures using the ensembles of strong ground motion records generated in Phase 1. These analyses will be conducted as part of several integrated research projects within MCEER that are looking at enhancing the seismic performance of structural systems through seismic response control technologies, as described in this paper. This floor acceleration database represents demand functions for various seismic hazard levels, locations, floor levels, and structural framing systems incorporating various seismic response control technologies (e.g. passive damping, base isolation, etc.).

3.3. Taxonomy of Nonstructural components in MCEER Demonstration Hospitals

Taxonomy of the most important nonstructural components in the two MCEER demonstration hospitals will be developed. Information will be collected from available MCEER data and from information available in the literature.

3.4. Experimental Assessment of Seismic Fragility of Nonstructural Components

Seismic (shake table) tests will be conducted on acceleration-sensitive nonstructural components typically contained in the MCEER hospital test beds and other acute care facilities, as determined in Phase 3 of the research. The shake table floor motions used for the seismic testing will be obtained from Phase 2 of the research. Donation will be sought to obtain representative nonstructural components. A general purpose shake table testing platform will be constructed. The shake table testing will incorporate various phases including different locations, seismic hazards, floor levels, and nonstructural components with and without seismic protection/restraint systems incorporated. The results of the shake table testing will provide guidance on the seismic design and retrofit of nonstructural components and will allow the construction of experimental seismic fragility curves for various limit states.

3.5. Formulation of Structural Design Objectives

Once the relationship between the seismic fragility of nonstructural components and the structural demands has been established, structural design objectives can be established for various target probability of failures of nonstructural components. These structural design objectives can then be used to optimize the structural design of acute care facilities using particular seismic response control technologies, thereby providing a feedback loop to the research projects described in this paper. Furthermore, this fragility information represents a critical component to be implemented in the decision support methodologies for acute care facilities currently under development at MCEER.

4.0 CONCLUSIONS

This paper has described briefly the integrated research currently underway at MCEER to better understand the applications of various seismic response control technologies to protect structural and nonstructural systems and components in acute care facilities from the effects of earthquakes. This innovative work is on schedule to deliver by year 10 robust and applicable decision support methodologies for enhancing the seismic resilience of acute care facilities.

5.0 ACKNOWLEDGMENTS

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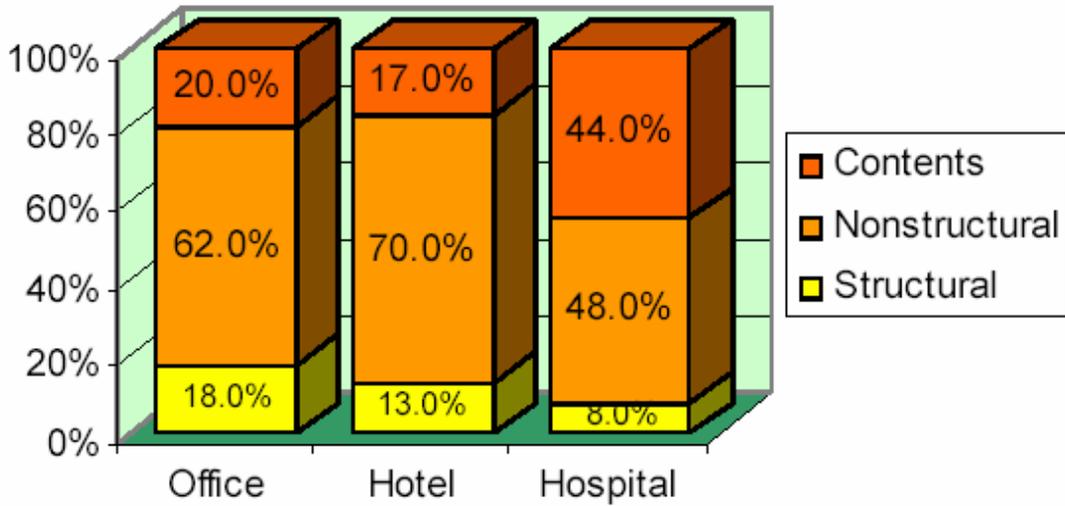
Figure 1: Investments in Building Construction (Miranda 2003).

a) Curves for peak ground acceleration

b) Curves for spectral acceleration at 1.5 seconds
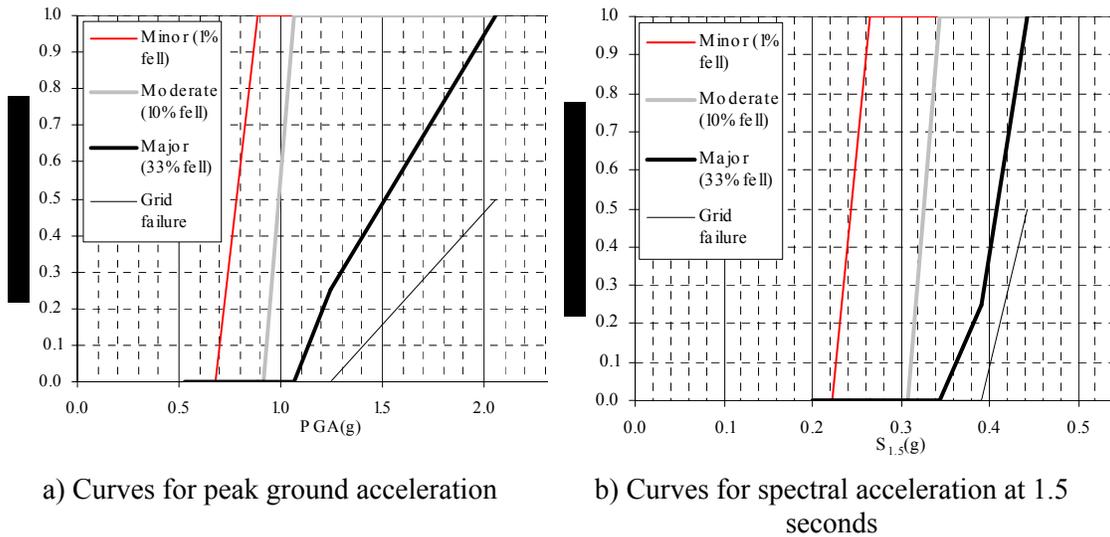
Figure 2: Sample Experimental Fragility Curves for Suspended Ceiling Systems (SCS).
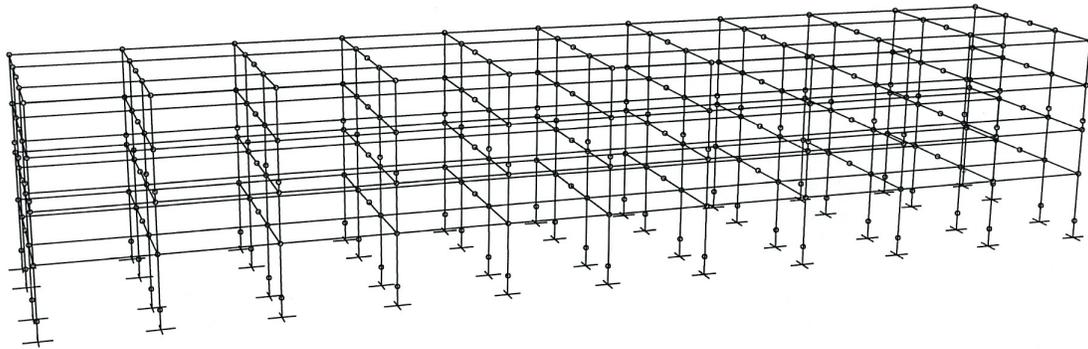
Figure 3: Three-Dimensional Numerical Model of
MCEER West Coast Demonstration Hospital WC70 Building
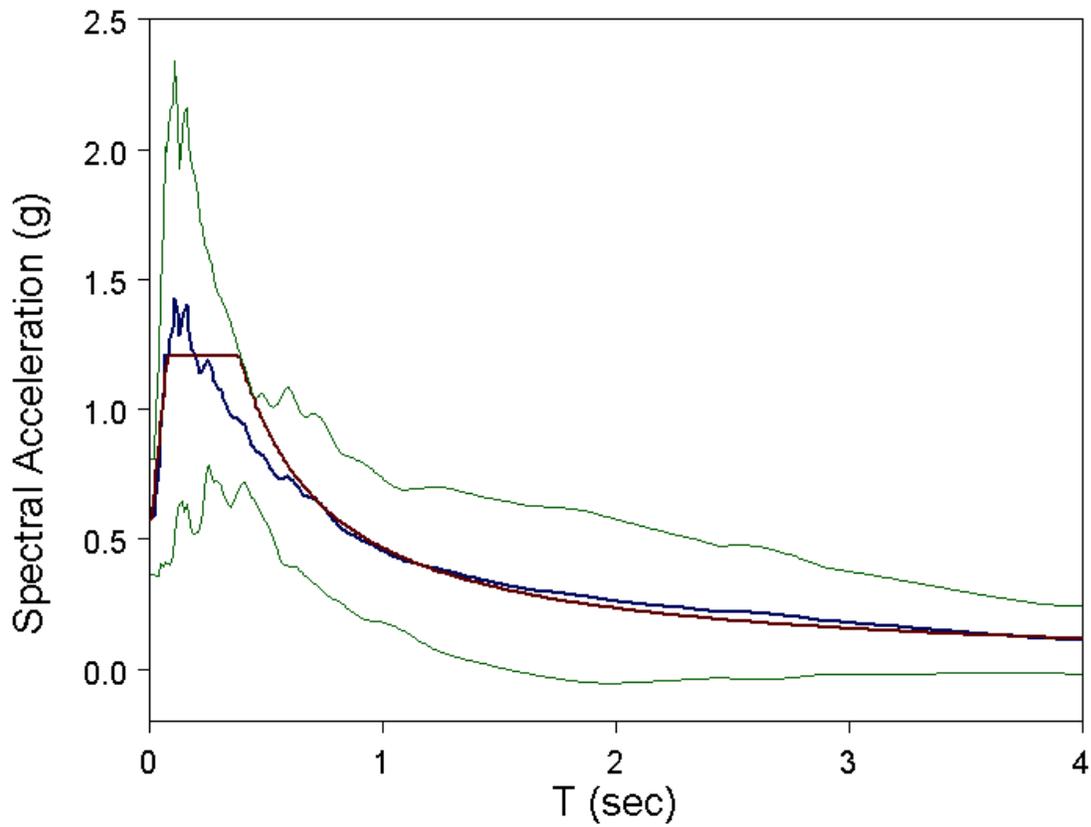
Figure 4: Target, Median, Maximum and Minimum 5% Damped Spectral Acceleration Ordinates for 20
Historical Ground Motion Time-Histories.
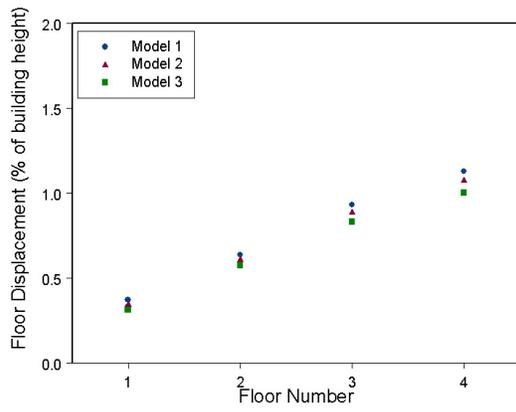
Joint Modeling Assumptions   Ground Motion Variability
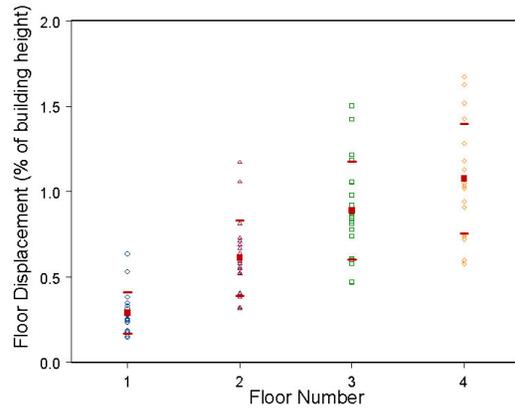
Figure 5: Dispersion in Floor Absolute Displacements for WC70 Building Excited by
20 Historical Ground Motion Time-Histories.
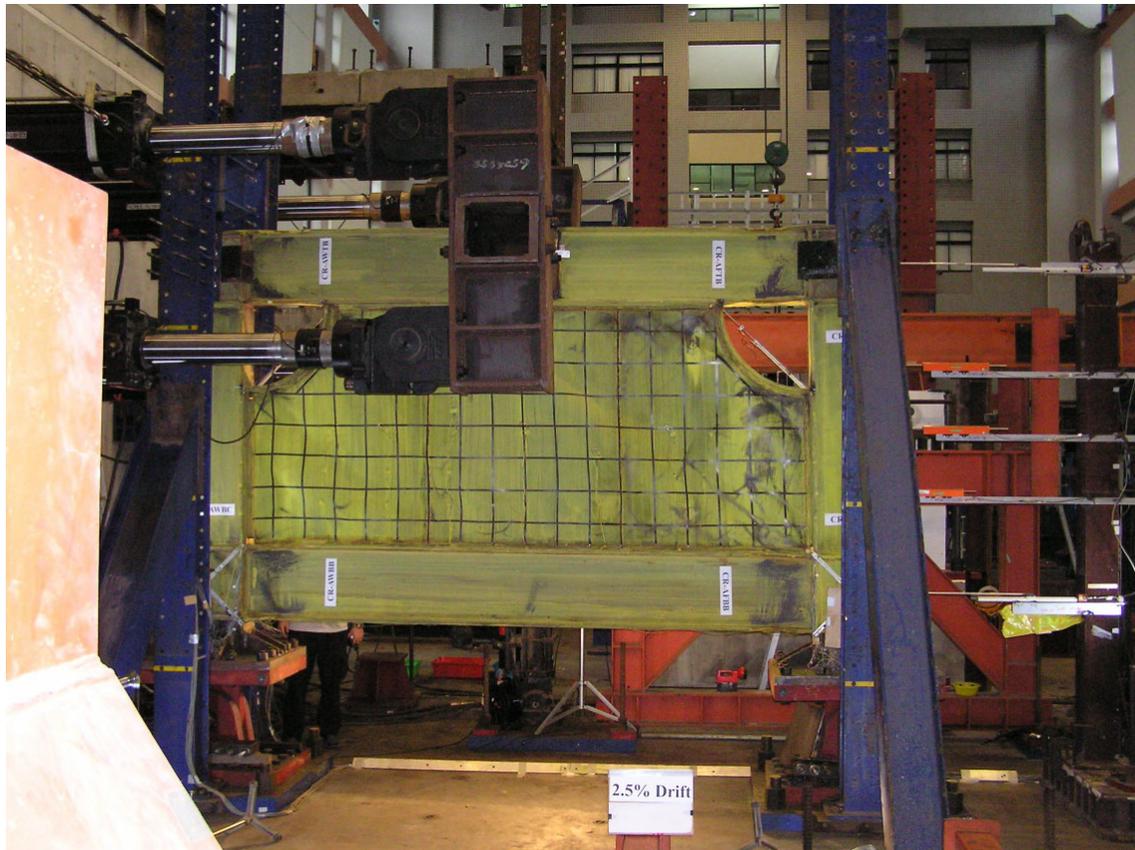
Figure 6: SPW Specimen with Cutout Corners to Accommodate Nonstructural Systems.
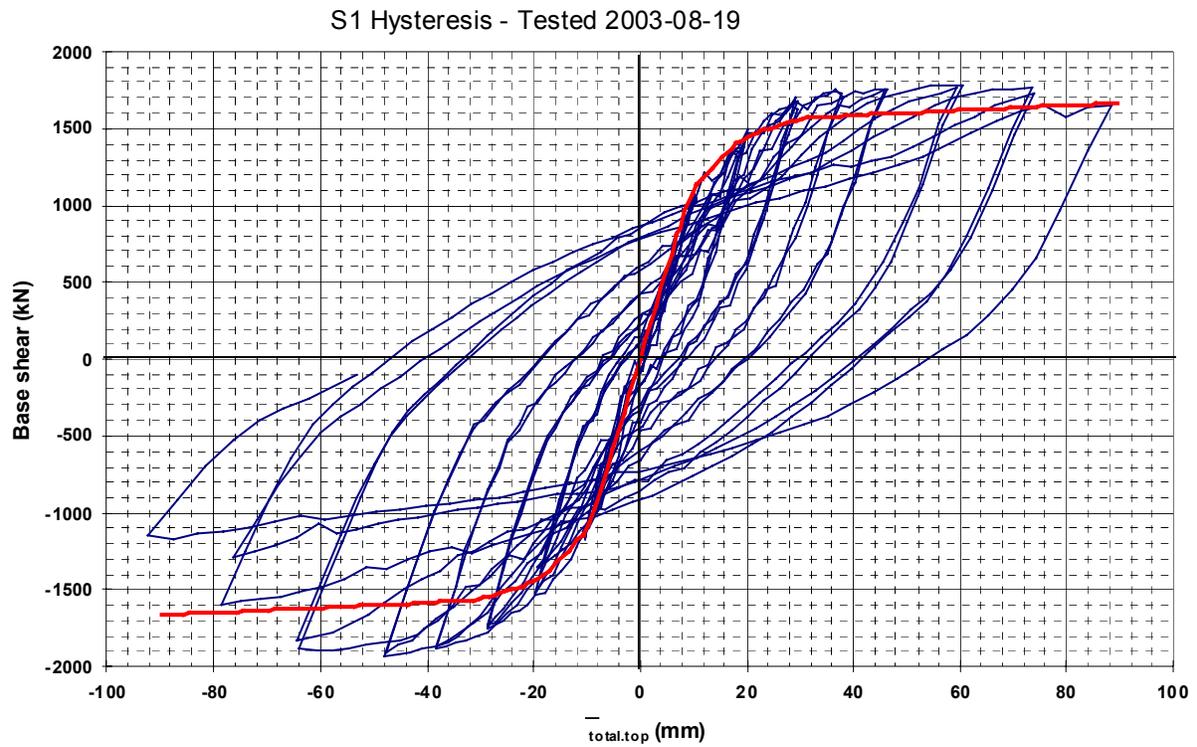
Figure 7: Hysteresis Loops for Solid Panel Specimen S1.

Buckled Panel Following Test   RBS Yielding

Figure 8: Buckled Panel and RBS Yielding of SPW Specimen.
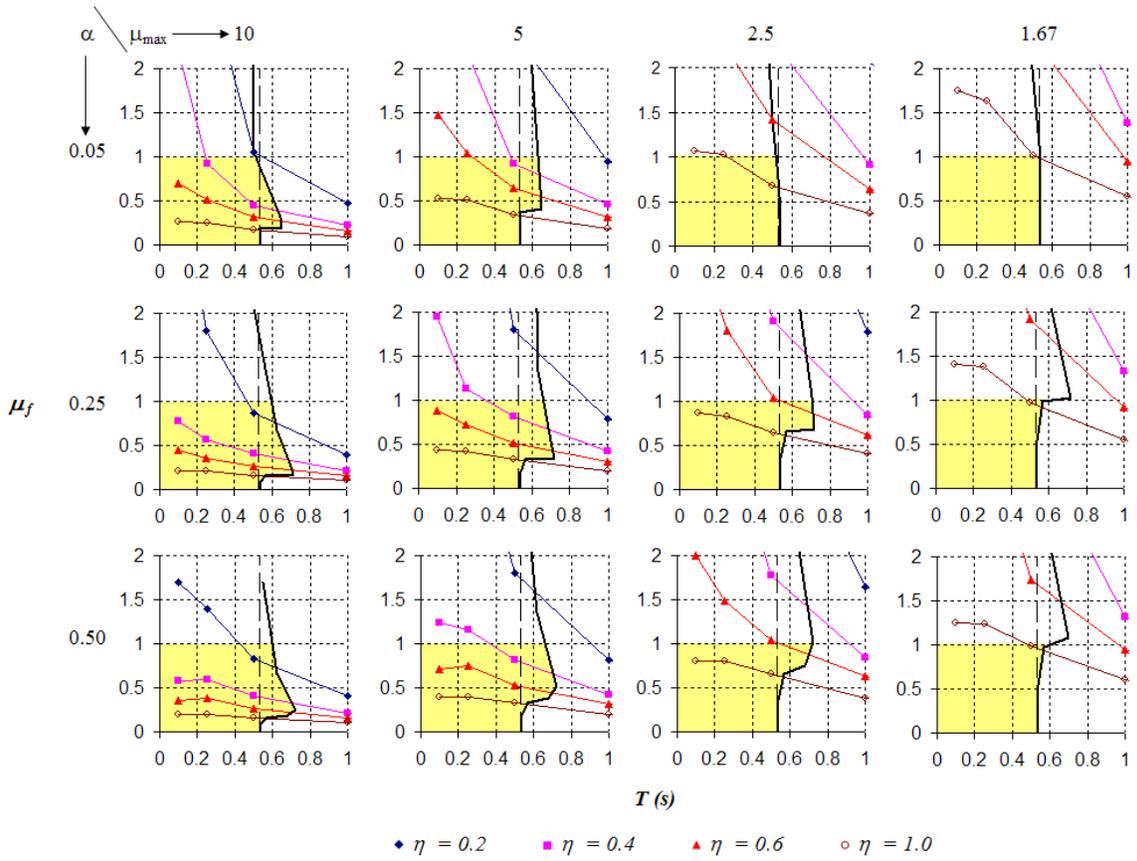
Figure 9: Dimensionless Metallic System response in Terms of Global and Local Ductility Demand, as a Function of Selected Key Design Parameters.

3-Story Frame without Damping System
V_y = 2220 to 2775 kN, T_1 = 1.07 sec
Special Steel Moment Frame
3S-Undamped

3-Story Frame with Damping System
V_y = 1300 to 1585 kN, T_1 = 1.58 sec
Special Steel Moment Frame
3S75-LV10%
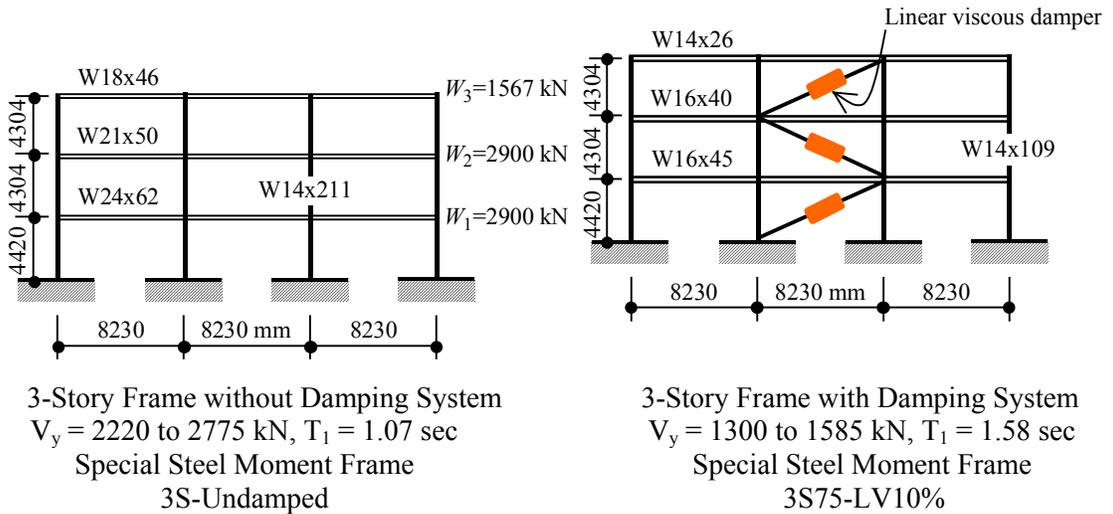
Figure 10: Example of Undamped (Left) and Damped Frames (Right).
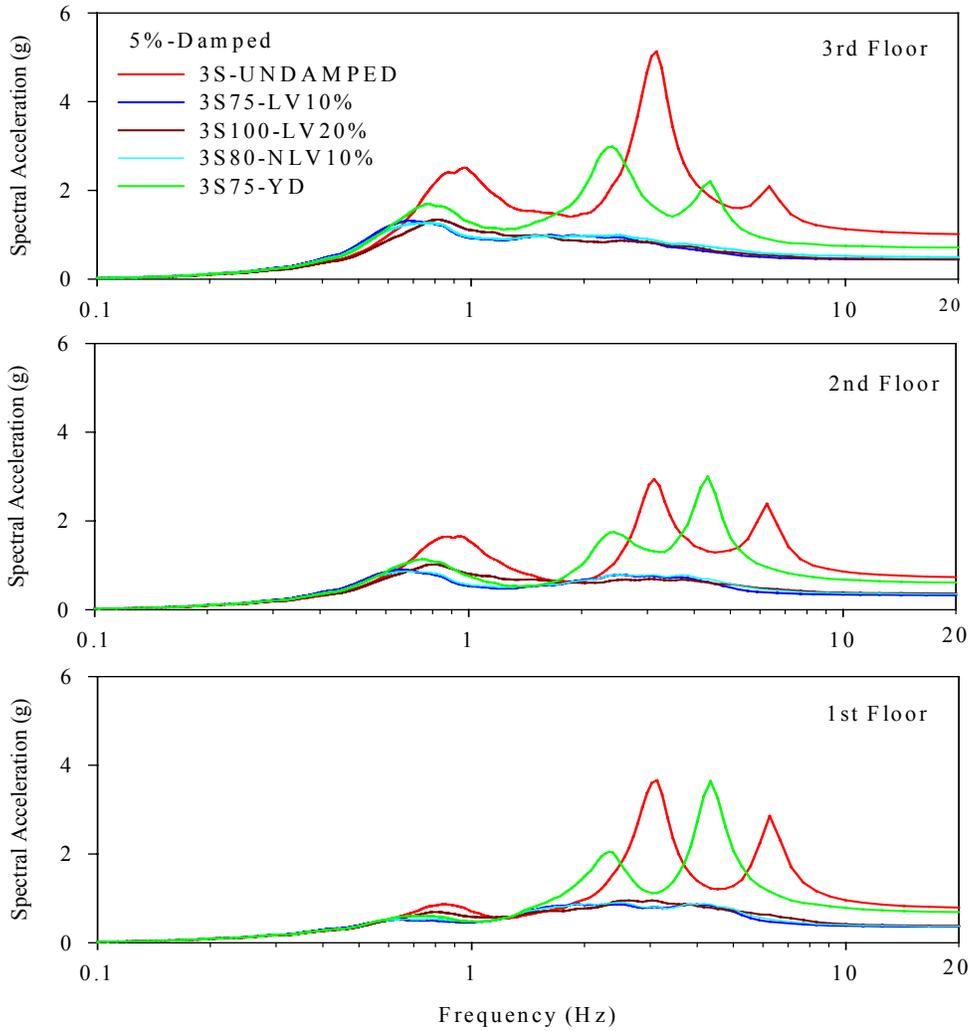
Figure 11: Floor Response Spectra in Damped and Undamped Structures.
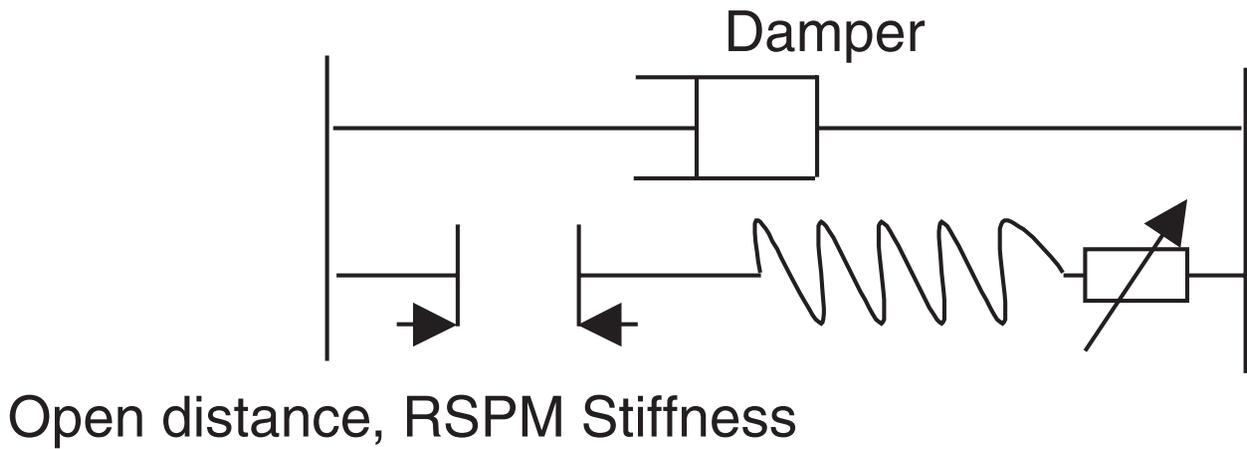
Figure 12: Combined RSPM and Passive Damping Hybrid Control System.
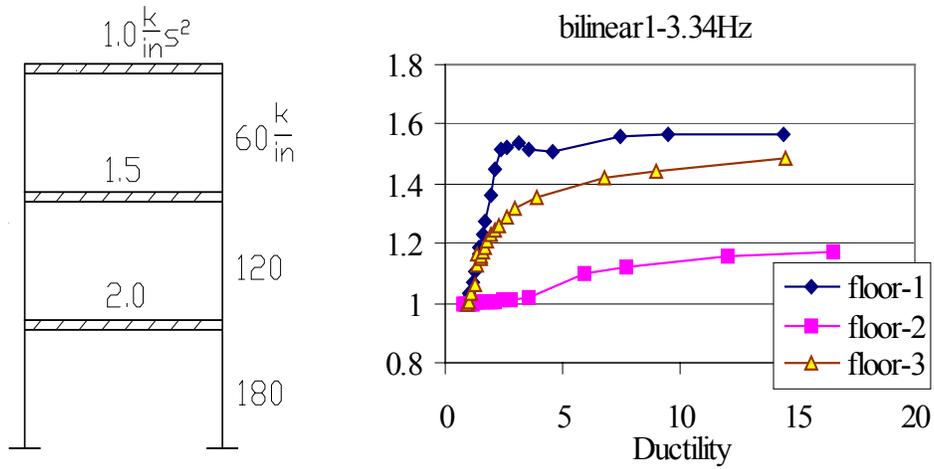
Figure 13: Variation of η with Ductility for a Three-Story Frame Model.
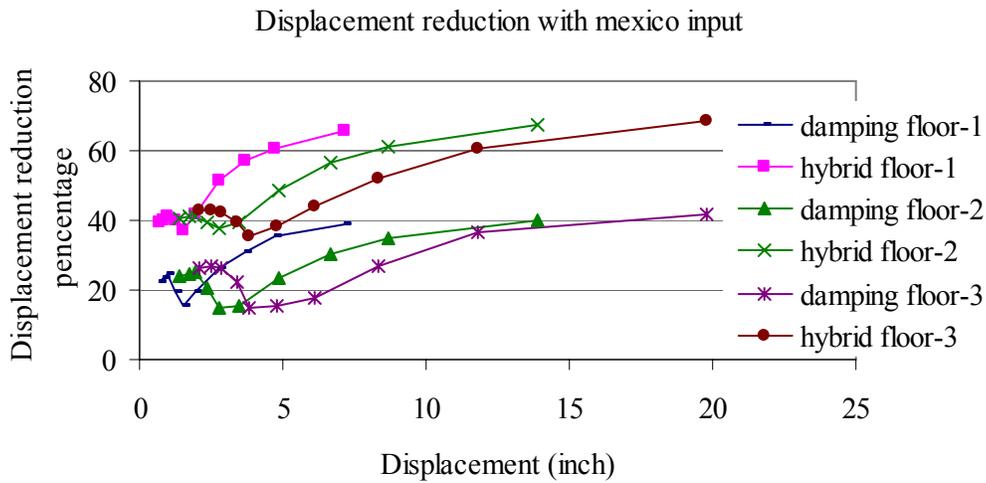
Figure 14: Seismic Response of Passive Damper and Hybrid Control System.
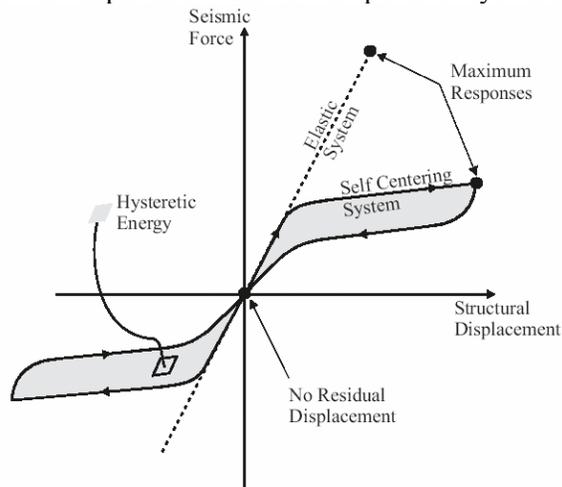
Figure 15: Idealized Seismic Response of Self-Centering Structures (Christopoulos et al. 2002a).
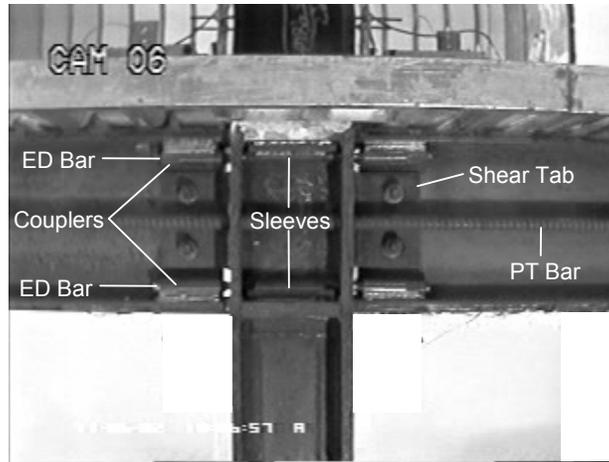
Figure 16: Concept of PTED Moment-resisting Steel Frames (Christopoulos et al. 2002b).
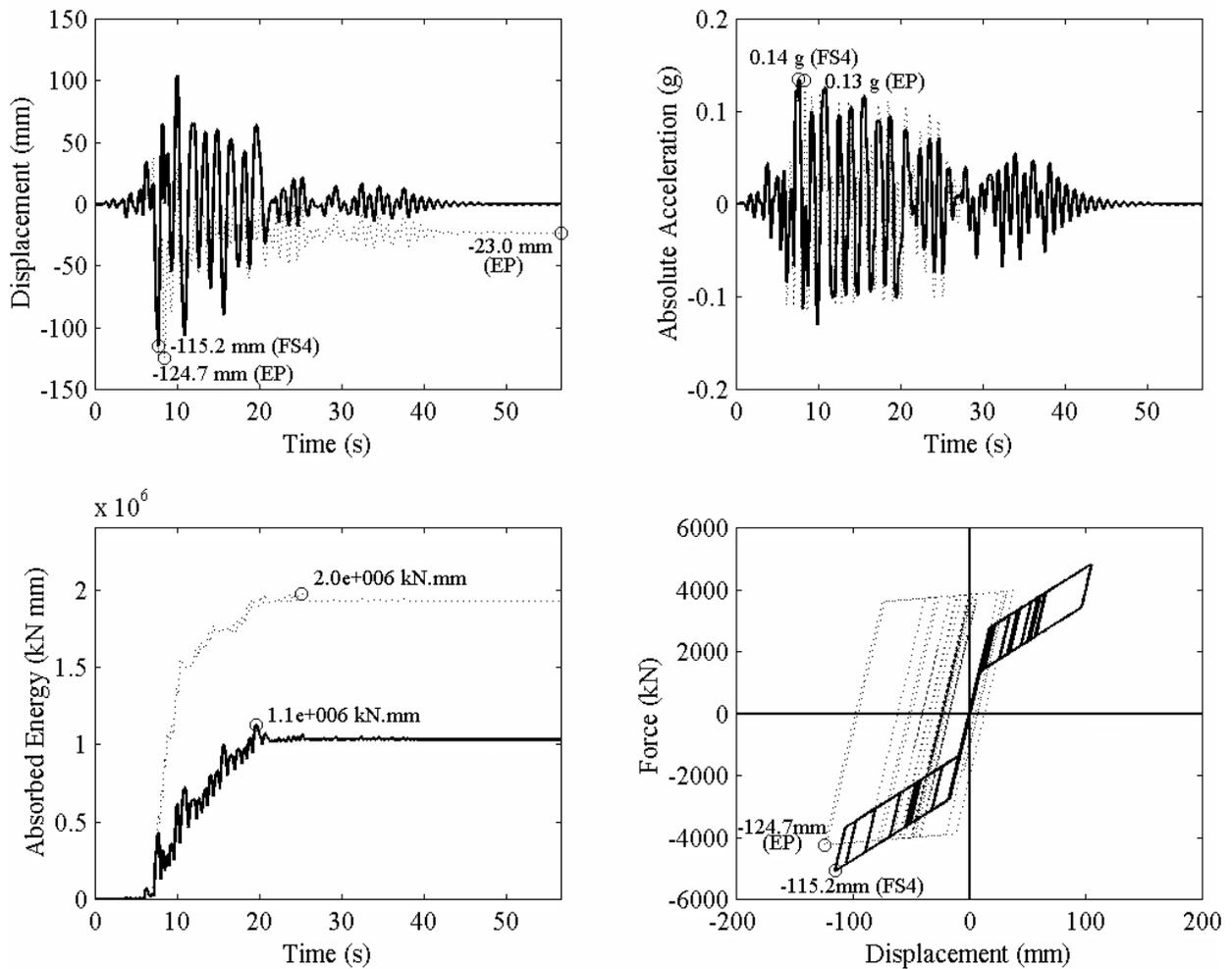
Figure 17: Comparative Seismic Response of Elasto-Plastic (EP) and Flagged-Shaped (FS4) Systems, 130% Loma Prieta (Hollister Differential Array) Record, a) Relative Displacement Time-Histories, b) Absolute Acceleration Time-Histories, c) Absorbed Energy Time-Histories, and d) Force-Displacement Responses (Christopoulos et al. 2002a).
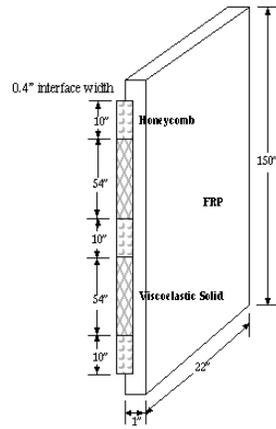
Figure 18: Details of Interface Layer of PMC Infill System.
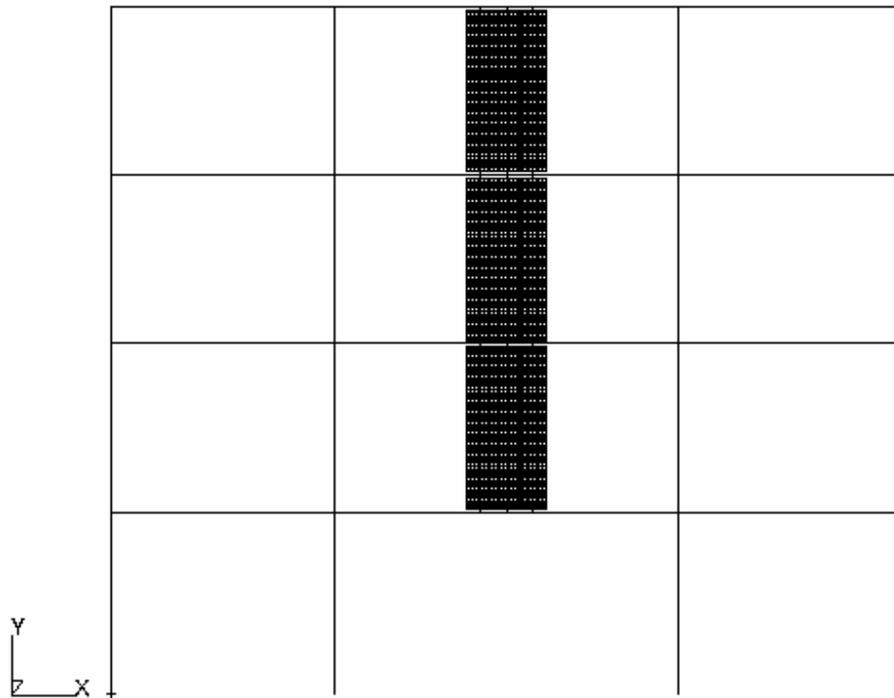
Figure 19: FE Model of Moment-Resisting Frame of MCEER West-Coast Demonstration Hospital with PMC panels in Central Bay.
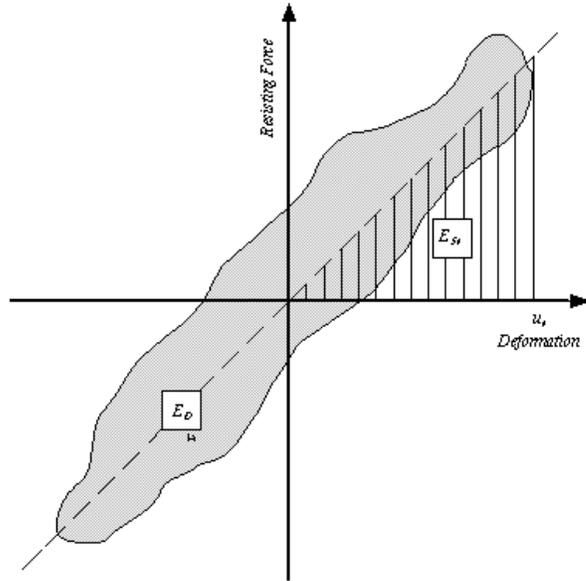
Figure 20: Global Hysteretic Response of Frame with PMC Panels.

▨	: Deep beam element
▧	: Deep column element
▨	: Rigid zone
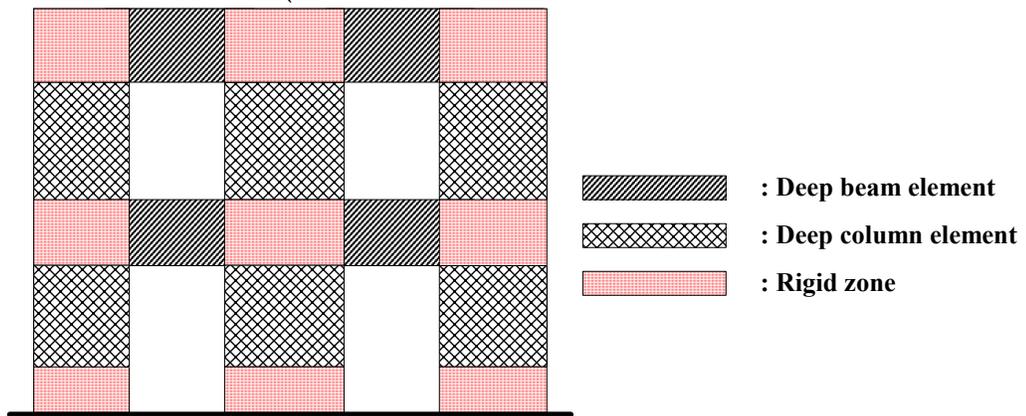
Figure 21: Model for Shear Wall with Regular Openings (Perforated Walls).
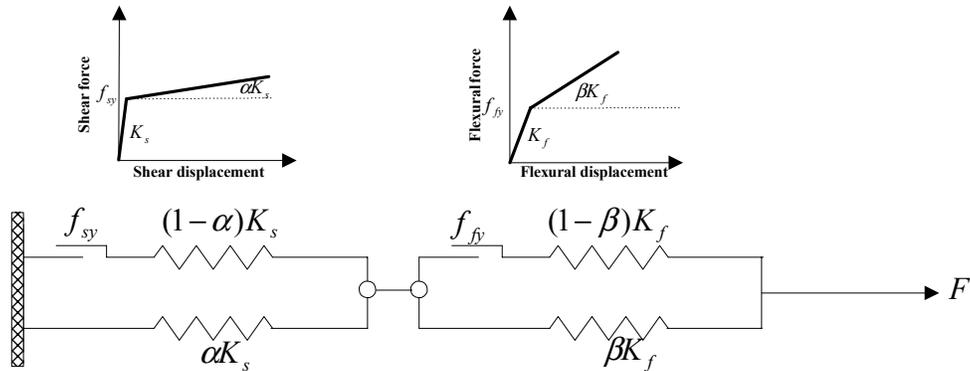
Figure 22: Macro-Model of Flexural-Shear Element.
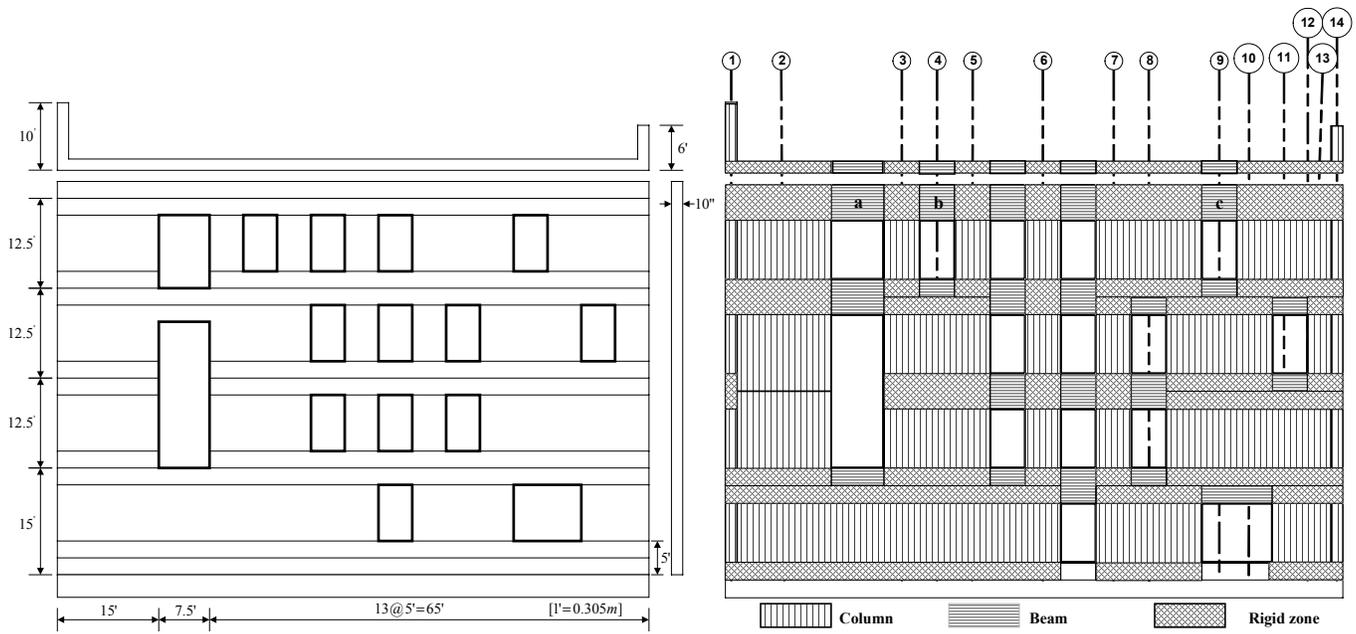
Figure 23: Shear Wall with Openings Case Study, Geometry (Left) and Model (Right).
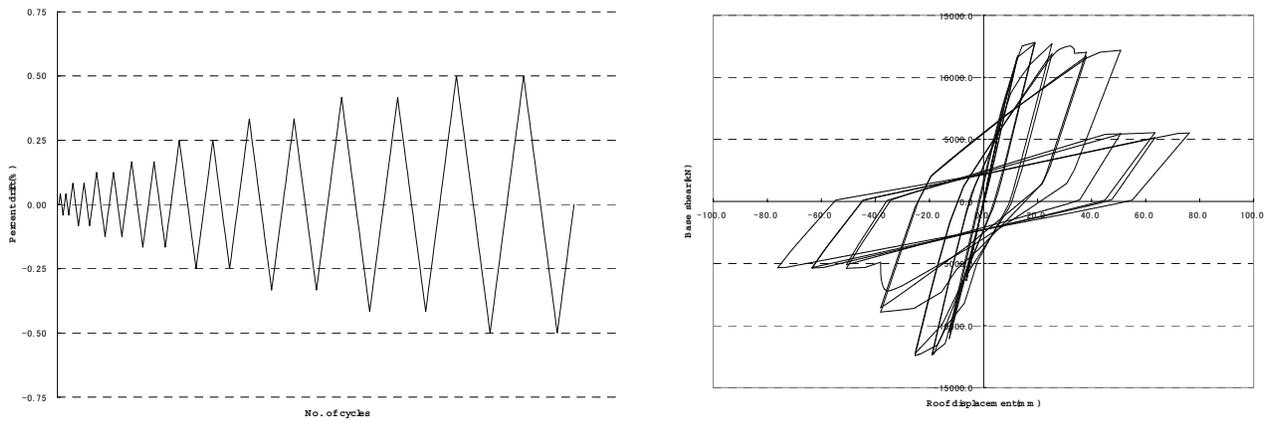
Figure 24: Shear Wall with Openings Case Study, Lateral Lading (Left)
Hysteretic Response (Right).